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This paper is dedicated to our dear colleague, the late Dr. Bahman Eghball.

Annual carbon dioxide exchange in irrigated and rainfed maize-based agroecosystems

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Abstract

Carbon dioxide exchange was quantified in maize–soybean agroecosystems employing year-round tower eddy covariance flux systems and measurements of soil C stocks, CO_2 fluxes from the soil surface, plant biomass, and litter decomposition. Measurements were made in three cropping systems: (a) irrigated continuous maize, (b) irrigated maize–soybean rotation, and (c) rainfed maize–soybean rotation during 2001–2004. Because of a variable cropping history, all three sites were uniformly tilled by disking prior to initiation of the study. Since then, all sites are under no-till, and crop and soil management follow best management practices prescribed for production-scale systems. Cumulative daily gain of C by the crops (from planting to physiological maturity), determined from the measured eddy covariance CO_2 fluxes and estimated heterotrophic respiration, compared well with the measured total above and belowground biomass. Two contrasting features of maize and soybean CO_2 exchange are notable. The value of integrated GPP (gross primary productivity) for both irrigated and rainfed maize over the growing season was substantially larger (ca. 2:1 ratio) than that for soybean. Also, soybean lost a larger portion (0.80–0.85) of GPP as ecosystem respiration (due, in part, to the large amount of maize residue from the previous year), as compared to maize (0.55–0.65). Therefore, the seasonally integrated NEP (net ecosystem production) in maize was larger by a 4:1 ratio (approximately), as compared to soybean. Enhanced soil moisture conditions in the irrigated maize and soybean fields caused an increase in ecosystem respiration, thus eliminating any advantage of increased GPP and giving about the same values for the growing season NEP as the rainfed fields. On an annual basis, the NEP of irrigated continuous maize was 517, 424, and 381 g C m^{-2} $year^{-1}$, respectively, during the 3 years of our study. In rainfed maize the annual NEP was 510 and 397 g C m^{-2} $year^{-1}$ in years 1 and 3, respectively. The annual NEP in the irrigated and rainfed soybean fields were in the range of −18 to −48 g C m^{-2}. Accounting for the grain C removed during harvest and the CO_2

released from irrigation water, our tower eddy covariance flux data over the first 3 years suggest that, at this time: (a) the rainfed maize–soybean rotation system is C neutral, (b) the irrigated continuous maize is nearly C neutral or a slight source of C, and (c) the irrigated maize–soybean rotation is a moderate source of C. Direct measurement of soil C stocks could not detect a statistically significant change in soil organic carbon during the first 3 years of no-till farming in these three cropping systems.

Keywords: carbon sequestration, carbon budget, no-till farming, eddy covariance

1. Introduction

One way to mitigate the increase in the atmospheric carbon dioxide (CO_2) concentration, at least in the short term, is to remove it from the atmosphere by increasing the carbon (C) uptake (or C sequestration) in terrestrial ecosystems (e.g., Caldeira et al., 2004). Cropland represents about 12% of the earth's surface (Wood et al., 2000), and in general, can have equal or greater net ecosystem production (NEP) than the natural ecosystems that were converted for crop production (e.g., Law et al., 2002, Barford et al., 2003 and Hollinger et al., 2004). A key scientific issue, therefore, is the quantification of C sequestration in highly productive cropland based on data obtained from production-scale agricultural systems.

Historically, conversion of native ecosystems to cropland has resulted in a substantial reduction in soil organic matter (e.g., Schlesinger, 1986 and Houghton et al., 1983). However, agricultural management practices have changed markedly during the last four decades with decreased tillage and increased crop yields and input use efficiency (Cassman et al., 2002). These changes affect the NEP of the agroecosystem, the amount of C that is incorporated into plant biomass, litter, and soil organic carbon (SOC). Despite rapid technological change in agricultural systems, there is little quantitative information available on the actual amounts of C sequestered in maize-based cropping systems, which represent the dominant agricultural land use in the north-central USA. Conservation tillage, reduced bare fallow, improved fertilizer management, crop rotation, and cover crops are factors commonly cited as having the greatest potential to increase soil C sequestration in agricultural systems (IPCC, 2000 and Lal et al., 2003). However, most of the published estimates have been obtained from long-term experiments conducted on relatively small plots or from simulation studies (e.g., Paustian et al., 1997 and West and Post, 2002). Many of these long-term experiments represent cropping systems that give average yields with average crop management, despite the fact that yields and biomass accumulation of the major food crops have increased steadily due to genetic improvement and improved management of soil and inputs (Cassman et al., 2003).

Given the dynamic technological change in maize-based cropping systems and the lack of detailed measurements of C flux in these systems, we initiated a set of production-scale field studies on three maize-based agroecosystems, which represent the major cropping systems in the western USA Corn Belt. The three fields are under no-till management. In each of these systems, progressive crop management practices were employed to optimize crop yields, input use efficiencies, and C sequestration. These studies include year-round landscape-level CO_2 flux measurements using tower eddy covariance flux sensors, as well as detailed plant- and soil-based process level investigations to quantify C cycling. The three cropping systems are: (1) irrigated continuous maize (*Zea mays* L.), (2) irrigated maize–soybean (*Glycine max* [L.] Merr.) rotation, and (3) rainfed maize–soybean rotation. The objective of this paper is to report results from the first 3 years of annually integrated NEP measurements from the tower flux systems, fine-scale mapping of soil C stocks, and related studies. With concurrent measurements in the three cropping systems (mentioned above), we address the following questions: (a) How does the seasonal and annual CO_2 exchange of maize compare with that of soybean? (b) What is the impact of irrigation on the CO_2 exchange of these crops? (c) How does the annual CO_2 exchange of a continuous maize system compare with a maize–soybean rotation?

2. Materials and methods

2.1. Study sites

The study sites are located at the University of Nebraska Agricultural Research and Development Center near Mead, NE. These sites are large production fields, each 49–65 ha, that provide sufficient upwind fetch of uniform cover required for adequately measuring mass and energy fluxes using tower eddy covariance systems. Two sites (1: 41°09′54.2″N, 96°28′35.9″W, 361 m; 2: 41°09′53.5″N, 96°28′12.3″W, 362 m) are equipped with center-pivot irrigation systems while the third site (3: 41°10′46.8″N, 96°26′22.7″W, 362 m) relies on rainfall. The three sites are within 1.6 km of each other. All measurements reported here refer to the irrigated areas at Sites 1 (48.7 ha) and 2 (52.4 ha) and the entire field area for the rainfed Site 3 (65.4 ha). Prior to initiation of the study, the irrigated sites (1 and 2) had a 10-year history of maize–soybean rotation under no-till. The rainfed site (3) had a variable cropping history of primarily wheat, soybean, oats, and maize grown in 2–4 ha plots with tillage. All three sites were uniformly tilled by disking prior to initiation of the study to homogenize the top 0.1 m of soil and incorporate P and K fertilizers, as well as previously accumulated surface residues. The soils are deep silty clay loams, typical of eastern Nebraska, consisting of four soil series at all three sites: Yutan (fine-silty, mixed, superactive, mesic Mollic Hapludalfs), Tomek (fine, smectitic, mesic Pachic Argialbolls), Filbert (fine, smectitic, mesic Vertic Argialbolls), and Filmore (fine, smectitic, mesic Vertic Argialbolls).

Since initiation in 2001, all sites have been under no-till. Under this system, seed was planted directly below the existing crop residue of the previous year with no soil disturbance except for the action of the planter opening a narrow slot for seed placement. Crop management practices (i.e., plant populations, herbicide and pesticide applications, irrigation) have been employed in accordance with standard best management practices (BMPs) prescribed for production-scale maize systems. Table 1 summarizes major crop management information (including the dates of planting and harvest, cultivars planted, and average crop yields) for the 2001–2003 period. To account for differences in water-limited attainable yield, plant densities were lower in rainfed crops at Site 3 than in irrigated crops at Sites 1 and 2, which follows best management practices. Nitrogen (N) was applied as urea ammonium nitrate solution. Under irrigation, N was applied in three applications (2/3 pre-plant and 1/3 as two fertigations through the sprinkler system) to improve N use efficiency. In contrast, a single N fertilizer application was made to maize in the rainfed system. Total N fertilizer rates for both the irrigated and rainfed sites were adjusted for residual nitrate measured in soil samples taken each spring before planting following recommended guidelines (Shapiro et al., 2001).

Our measurements began around the planting time in 2001. Within each site, six small measure-

Table 1. Crop management details and grain yield for the three sites during 2001–2003 (M, maize; S, soybean; maize grain yield: adjusted to 15.5% moisture content; soybean grain yield: adjusted to 13% moisture content)

Site/year	Crop/cultivar	Plant population (plants/ha)	Planting date	Harvest date	Applied N (kg N ha^{-1})	Grain yield (Mg ha^{-1})
1 Irrigated continuous maize (48.7 ha)						
2001	M/Pioneer 33P67	82,000	May 10	October 18	196	13.51
2002	M/Pioneer 33P67	81,000	May 9	November 4	214	12.97
2003	M/Pioneer 33B51	77,000	May 15	October 27	233	12.12
2 Irrigated maize–soybean rotation (52.4 ha)						
2001	M/Pioneer 33P67	81,000	May 11	October 22	196	13.41
2002	S/Asgrow 2703	153,000	May 20	October 7	0	3.99
2003	M/Pioneer 33B51	78,000	May 14	October 23	169	14.00
3 Rainfed maize–soybean rotation (65.4 ha)						
2001	M/Pioneer 33B51	53,000	May 14	October 29	128	8.72
2002	S/Asgrow 2703	156,000	May 20	October 9	0	3.32
2003	M/Pioneer 33B51	58,000	May 13	October 13	90	7.72

ment areas (intensive measurement zones, IMZs) 20 m × 20 m each, were established for detailed process-level studies of soil C dynamics, crop growth and biomass partitioning, belowground C deposition, soil moisture, canopy and soil gas exchange, and crop residue decomposition. The locations were selected using fuzzy-*k*-means clustering (Minasny and McBratney, 2003) applied to six layers of previously collected, spatially dense (4 m × 4 m cells) information (e.g., elevation, soil type, electrical conductivity, soil organic matter content, digital aerial photographs, NIR band of multispectral IKONOS satellite images). Six (Sites 1 and 2) or five (Site 3) spatial fuzzy classes were delineated to represent the spatial variation in soil type, other landscape features, and crop production potential within each site as a basis for accurate upscaling of ground measurements to the whole-field level. The IMZ locations were chosen to represent each of those fuzzy classes. For example, at Site 1, two IMZs represented the two fuzzy classes primarily found on summit or shoulder positions, characterized mainly by more eroded soils, lower soil organic matter content, and drier soil conditions. In contrast, two fuzzy classes occurring in low-lying areas with deeper soils, greater soil moisture, and higher organic matter content were represented by two other IMZs. Soil water conditions in the root zone were monitored continuously at four depths (0.10, 0.25, 0.5, and 1.0 m) in four IMZs at each site employing Theta probes (Delta-T Devices, Cambridge, UK). Other measurements are described below.

2.2. Eddy covariance flux measurements

Eddy covariance measurements (e.g., Baldocchi et al., 1988) of fluxes of CO_2, water vapor, sensible heat, and momentum were made using the following sensors at the three sites: an omnidirectional 3D sonic anemometer (Model R3: Gill Instruments Ltd., Lymington, UK), a closed-path infrared CO_2/H_2O gas analyzing system (Model LI6262: Li-Cor Inc., Lincoln, NE), and a krypton hygrometer (Model KH20: Campbell Scientific, Logan, UT). To have sufficient fetch (in all directions) representative of the cropping systems being studied, the eddy covariance sensors were mounted 3.0 m above the ground when the canopy was shorter than 1 m, and later moved to a height of 6.0 m until harvest (maize only). Fluxes were corrected for inadequate sensor frequency response (Moore, 1986, Massman, 1991 and Suyker and Verma, 1993; in conjunction with cospectra calculated from this study). Fluxes were adjusted for the variation in air density due to the transfer of water vapor (e.g., Webb et al., 1980). More details of the measurements and calculations are given in a previous paper (Suyker et al., 2003). The CO_2 storage, calculated from CO_2 profiles, was incorporated with the eddy flux term to calculate the net ecosystem production, NEP (NEP is equal but opposite in sign to NEE, the net ecosystem CO_2 exchange). In year 1, we did not have CO_2 profile data and so the CO_2 storage term was estimated based on concentration measured at 6.0 m. Air temperature and humidity (3.0 and 6.0 m; Humitter50Y, Vaisala, Helsinki, Finland), soil temperature (0.06, 0.1, and 0.2 m depths; platinum RTD, Omega Engineering, Stamford, CT), photosynthetically active radiation (LI 190SA Quantum sensor, Li-Cor Inc.), net radiation at 5.5 m (Q^* 7.1, Radiation and Energy Balance Systems Inc., Seattle, WA), and soil heat flux (0.06 m depth; Radiation & Energy Balance Systems Inc.) were also measured.

To fill in missing data due to sensor malfunction, power outages, etc., we adopted an approach that combined measurement, interpolation, and empirical data synthesis (e.g., Kim et al., 1992, Wofsy et al., 1993, Baldocchi et al., 1997 and Suyker et al., 2003). When daytime hourly values were missing, the CO_2 flux was estimated as a function of photosynthetically active radiation (PAR) during the day (or the adjacent day, if needed). To minimize problems related to insufficient turbulent mixing at night, following an analysis similar to Barford et al. (2003), we selected a threshold mean windspeed (U) of 2.5 m s^{-1} (corresponding to a friction velocity, u_* of 0.25 m s^{-1}, approximately). For $U < 2.5$ m s^{-1}, data were filled in using bi-weekly CO_2 exchange temperature relationships from windier conditions. Daytime estimates of ecosystem respiration (R_e) were obtained from the night CO_2 exchange temperature relationship (e.g., Xu and Baldocchi, 2003). The gross primary productivity (GPP) was then obtained by subtracting R_e from NEP (sign convention used here is such that CO_2 flux to the surface is positive so that GPP is always positive and R_e is always negative).

2.3. Energy balance closure

It is customary to compare the sum of latent and sensible heat fluxes (LE + H) measured by eddy covariance against the sum of R_n (net radiation) + storage terms, measured by other methods. As Meyers and Hollinger (2004) point out, the combination of soil and canopy heat storage and the energy used in photosynthesis in maize and soybean need to be considered for an accurate estimation of the energy balance closure. We calculated linear regressions between the hourly values of H + LE and $R_n + G$ for our three study sites during the 3 years of measurements (excluding winter months and periods with rain and irrigation). Here $G = G_s$ (soil heat storage) + G_c (canopy heat storage) + G_m (heat stored in the mulch) + G_p (energy used in photosynthesis). These terms were estimated using procedures similar to those outlined in Meyers and Hollinger (2004). The regression slopes ranged from 0.91 to 1.05, implying a fairly good closure of the energy balance at our study sites.

2.4. Estimation of heterotrophic soil respiration (R_h)

Daily R_h (the heterotrophic component of total soil respiration) was estimated in two ways: (a) using bi-weekly chamber CO_2 flux measurements at the soil surface (F_s) and (b) using night eddy covariance CO_2 exchange data, with adjustment for plant respiration based on concurrent measurements of leaf gas exchange at the study sites and night/day temperatures. Chamber F_s data were fitted to an exponential function (e.g., Norman et al., 1992) of soil temperature, soil moisture, and LAI for temporal interpolation. Two kinds of chambers [(i) a small chamber (8×10^{-4} m^{-3} in volume, model LI-6200, Li-Cor Inc., Lincoln, NE; e.g., Norman et al., 1992) and (ii) a larger chamber (9.3×10^{-2} m^{-3} in volume, as described by Hutchinson and Mosier, 1981)] were used to measure F_s. An average of the values from the two methods was used here. The proportion of F_s attributed to heterotrophic respiration (R_h) was estimated for the period between planting and physiological maturity from the difference between F_s from non-root excluded soil and a subset of flux measurement from root excluded soil measured within each IMZ. This proportion was then applied to all F_s measurements for temporal interpolation of R_h.

2.5. Monitoring soil C stocks

Changes in soil organic carbon (SOC) in the top 0.3 m of soil were measured by annual soil sampling conducted in April 2001, 2002, 2003 and 2004 in each IMZ. Within each IMZ, five separate samples were collected along a transect in east–west direction. At each transect location, two 32 mm × 300 mm soil cores were collected 0.5 m apart between previous crop rows. Each core was split into three depth segments of 0–0.05, 0.05–0.15, and 0.15–0.30 m, and the samples were combined into one composite sample per depth and sampling location. In other words, there were a total of 5 locations × 3 depths = 15 samples for C and N analysis in each IMZ or 90 samples for each site.

All soil samples were dried to a constant weight at 40 °C, completely passed through a 2 mm sieve, and recognizable undecomposed organic matter particles were removed. A sub-sample was fine-ground to 100 mesh using a roller mill. Twenty milligrams of fine-ground soil was weighed for soil organic carbon (SOC) analysis using an elemental analyzer (ECS 4010, Costech Analytical Technologies Inc., Valencia, CA).

None of the samples contained significant amounts of free $CaCO_3$. Based on repeated analysis of standard soil samples included in different batches, the CV of the C analysis was within the 1–3% range. At the same transect locations in each IMZ, an additional 21 mm × 300 mm soil core was taken with a lubricated plastic sleeve mounted inside a hand probe to determine bulk density. Each intact soil core was divided into three segments corresponding to the depths used for determining soil C, and soil from each segment was dried at 105 °C for 24 h and weighed.

Estimates of SOC (g C m^{-2}) were calculated for each of the three soil depth intervals based on the measured bulk density at the time of sampling and SOC mass fractions. Overall soil C stocks were calculated on cumulative dry soil mass basis (dried at 105 °C), following the approach described by Gifford and Roderick (2003). Two reference soil masses were used to evaluate SOC changes over time: (i) in the top 200 kg dry soil m^{-2} (approximately 0–0.15 m depth) and (ii) in the top 400 kg dry soil m^{-2} (approximately 0–0.30 m depth). Both values were calculated using Equation (4) in Gifford and Roderick (2003). Unlike fixed-soil volume

based estimates of SOC, the cumulative mass approach better accounts for the variation in effective sampling depth and soil mass due to changes in soil bulk density over time.

Whole-field estimates of SOC were obtained as spatially weighted means and standard errors, with the weight of each sampling location (IMZ) proportional to the relative field area occupied by the SOC class it represented. In 2001, SOC sampling was done at 202–265 locations per site and detailed (4 m × 4 m grid) SOC maps were obtained by simple kriging with varying local means (Simbahan, 2004). Using fuzzy-*k*-mean clustering, these maps were summarized in six spatial classes, which covered the range of SOC found at each site and formed the basis for assigning a weight to each IMZ based on its class membership. Estimates of the mean $\bar{x}$ and standard error $SE_{\bar{x}}$ for the whole field were obtained from the annual IMZ measurements of SOC by:

$$\bar{x} = \sum_{i=1}^{m} w_i \bar{x}_i, \quad w_i = \frac{\text{area of fuzzy class } k}{\text{total area}}, \sum w_i = 1 \tag{1}$$

$$SE_{\bar{x}} = \sqrt{\frac{1}{m}\sum_{i=1}^{m} w_i (x_i - \bar{x})^2 + \frac{1}{mn}\left(\frac{1}{m}\sum_{j=1}^{n}(x_{ij} - \bar{x}_i)^2\right)} \tag{2}$$

where w_i is the weight assigned to IMZ i, $\bar{x}_i$ is the IMZ mean, m is the number of IMZs per site, n is the number of replicates within an IMZ, and x_{ij} is the value of sample j within IMZ i.

2.6. Litter decomposition

Crop residues accumulate as surface litter in no-till systems. Total litter C input was estimated from the measured values of stover and root biomass taken at physiological maturity in each IMZ. Litter mass and C loss from the litter were measured at 6-month intervals, beginning after grain harvest, for a 3-year period using litterbags placed aboveground (Robertson and Paul, 2000 and Burgess et al., 2002) and a minicontainer system belowground (Paulus et al., 1999). A representative sample of plant biomass was collected a few days before the grain harvest, adjacent to each IMZ. Crop residues were separated into leaves, stems, cobs (maize), pods (soybean), belowground stem, course roots (≥4 mm), and fine roots (<4 mm). In each IMZ soon after grain harvest, approximately 10 g of each type of litter was placed in a nylon bag (mesh 1.5 mm) and left on the soil surface, with two replicates per litter type. Another set of litter samples was placed belowground at 0.05 m depth. Belowground samples included 0.2 g of each litter type placed into a container with four replicates. For the first litter cohort set placed after grain harvest in 2001, two mesh sizes were used for belowground containers: a fine mesh of 0.1 mm and a courser mesh of 2 mm. However, no significant differences in litter C loss rates were found between the mesh sizes so that litter cohorts placed after harvest in 2002 and 2003 were enclosed in the fine mesh only. All litter samples were analyzed for C with a Costech 4010 elemental analyzer.

The mass and C concentration of litter pools were estimated for each annual litter cohort set using an exponential decay model based on litter decomposition at 6-month intervals. For the two irrigated sites, the amount of annual standing residue was estimated with an exponential litter decay equation based on the measured litter C inputs from 2001 to 2003 and the amount of litter C plowed into the soil in the beginning of the study in spring 2001. The latter was estimated from the historical crop yields in each field since 1994 and the measured stover:grain and root:grain ratios from the current study. Such an estimate was not possible for Site 3 (rainfed maize–soybean rotation) because this field was divided into a number of smaller fields that were under different crop rotations and management regimes prior to 2001.

2.7. Above and belowground biomass and leaf area

Aboveground biomass and green leaf area were determined from destructive samples at 10- to 14-day intervals until physiological maturity and again just prior to harvest. One-meter linear row sections were destructively sampled in each IMZ. Standing root biomass of maize was measured at tasseling (VT) stage and physiological maturity (R6) in 18 transects per site (three per IMZ), each transect consisting of four cores taken to a depth

of 0.6 m (2001) and 1.2 m (2002 and 2003). Samples were taken in 0.15 m increments and root biomass below the 0.6 m or 1.2 m depth extrapolated by fitting an exponential decay function to measured values. Root biomass at times not physically measured was estimated from the hybrid-maize model (Yang et al., 2004), which contains a root biomass subroutine. Model estimates were adjusted to fit actual-measured aboveground biomass. Soil cores were carefully washed free of soil and organic residues, were stained with congo-red to visually separate live from dead material, and then hand sorted, dried, and weighed. A subsample of root material was analyzed for C with a Costech 4010 elemental analyzer. Standing root biomass of soybean was measured at R3 stage and physiological maturity with the same transect of cores described for maize. Total belowground C allocation (minus autotrophic respiration) included measured root biomass plus an estimate of 30% of standing root biomass as rhizosphere deposition (i.e., root exudation and fine root turnover) (Haller and Stolp, 1985 and Qian et al., 1997). For the purpose of conducting our biomass C balance, we assume that 30% of rhizosphere C deposition is retained in soil. Therefore, the belowground biomass C component of net plant carbon was calculated as 1.09 times measured standing root biomass C.

2.8. Grain yield, biomass and plant carbon at harvest

Grain yields for the whole-field area were measured by weighing the entire amount of grain removed during combine harvest and measuring grain moisture in each load. Final whole-field yield estimates were obtained by adjusting yield to a standard moisture content of 0.155 g H_2O g^{-1} grain biomass for maize and 0.13 g H_2O g^{-1} for soybean (Table 1) or expressing them on dry matter basis for C balance calculations. Scale-weight yields were within 0.5–1.5% of the average grain yield measured with a calibrated yield monitor mounted on the combine used for harvest.

In each field, hand harvest was conducted at 24 locations in each year, which included the six IMZs. At each location, six plants (maize) or 1 m of row (soybean) were sampled at physiological maturity to determine dry matter and C and N concentrations in plant tissue (grain, cobs or pod-walls, vegetative biomass). Samples were dried at 70 °C, ground and analyzed for C and N using a Costech ECS 4010 elemental analyzer. At harvest, all maize ears were hand-picked or soybean yield was measured with a small plot combine from a 9.3 m^2 harvest area (2 rows × 6.1 m). Harvest index and tissue C and N mass fractions measured in the hand-harvested samples were averaged for each site-year and used in combination with the whole-field grain yield estimate to calculate whole-field aboveground biomass, C removal with grain, and C input as crop residues remaining for each site.

2.9. CO_2 release from irrigation water

The CO_2 released from irrigation water was estimated from the metered amount of water applied each season and the CO_2 released per liter of water applied. The latter was estimated from irrigation water samples collected directly from the wellhead of Site 1 in August 2004 (pH 7.24, electric conductivity 1.14 mmho cm^{-1}). The water was sampled into syringes without airspace and kept at the temperature at which it was collected until it was used for measuring the CO_2 emission rate after application to soil. Total time from collection to application to soil was 3–4 h. A composite fresh soil sample was collected from the six IMZs of Site 1 (top 0.2 m, 21% moisture content, passed through a 5 mm sieve). Emission measurements were performed in the laboratory at 21 °C using four replicates, each containing 19 g fresh soil weighed into a stoppered 1 L flask. Two mL of irrigation water were injected into the flask using a 10 mL syringe. The CO_2 concentration within each flask was measured immediately before adding the water and after 1 h. Previous tests determined that emissions from added irrigation water reached equilibrium within this timeframe. Emission of CO_2 from distilled water, which was equilibrated in open air for 24 h and injected to fresh soil by the above procedure, was used as the control. The CO_2 concentration within the incubation flasks was measured with a Photoacoustic analyzer (1312 Photoacoustic Multi-Gas Monitor, AirTech Instruments, Ballerup, Denmark).

3. Results and discussion

3.1. Crop production and nitrogen use efficiency

Both crop yields and N fertilizer efficiencies achieved in the current study were substantially greater than average yields and efficiencies obtained by farmers. For example, irrigated maize yields ranged from 12.1 to 14.0 Mg ha^{-1} at Sites 1 and 2 (Table 1), compared to the average USA maize yield of 8.6 Mg ha^{-1}, or the average irrigated maize yield of 11.0 Mg ha^{-1} in Nebraska during the same years. Rainfed maize yield was 8.7 Mg ha^{-1} in 2001 and 7.7 Mg ha^{-1} in 2003 compared to the average rainfed maize yield in Nebraska of 6.9 and 5.2 Mg ha^{-1}, respectively. Soybean yields averaged 3.99 Mg ha^{-1} at Site 2 and 3.32 Mg ha^{-1} at Site 3. For comparison, national average soybean yield in 2002 was 2.66 Mg ha^{-1} and irrigated and rainfed Nebraska state averages were 3.56 and 2.65 Mg ha^{-1}, respectively. Average fertilizer N use efficiency of continuous, irrigated maize was 61 kg grain kg N^{-1} (Site 1), 76 kg kg^{-1} for maize in the maize–soybean rotation in Site 2, and 77 kg kg^{-1} in the rainfed maize–soybean rotation in Site 3. These values compare to a USA average for maize of about 58 kg kg^{-1} (Cassman et al., 2002). In summary, the three sites represented highly productive cropping systems in which BMPs were implemented in production-scale fields, resulting in both greater yields and higher N use efficiency than achieved by average maize and soybean farmers at both state and national levels.

3.2. Meteorological information, soil water, and leaf area

Air and soil temperatures (T_a, 6.0 m; T_s, 0.1 m depth), photosynthetically active radiation (PAR), precipitation, irrigation, soil water (top 1.0 m), and leaf area index at the three sites are included in Table 2. The growing seasons of years 1 and 2 (2001 and 2002) were slightly warmer than year 3 (2003). Year 2 had a considerably colder winter (October–February average T_a of 0.5–0.6 °C) as compared to the other 2 years. On an annual basis all three sites had similar temperatures. At the irrigated sites (1 and 2) sufficient soil water was maintained: the volumetric soil water averaged between 0.27 and 0.31 throughout the growing seasons. At the rainfed site (3), however, moisture stress was observed for 5 days in the growing season of year 1, 15 days in year 2, and 32 days in year 3 (i.e., the volumetric soil water was below 0.19, which is 50% of the maximum plant available soil water). The peak green leaf area index (LAI) was between 5.5 and 6.1 for irrigated maize, 3.9 and 4.3 for rainfed maize, and 5.5 and 3.0 for irrigated and rainfed soybean, respectively.

3.3. Net ecosystem production: tower eddy covariance CO_2 flux measurements

Daily values of NEP at the three sites for the first 3 years are shown in Figure 1. Generally, the ecosystem became a net sink for CO_2 in the second or third week of June (about 30–35 days after planting for maize and 25–30 days after planting for soybean). The maize fields remained a sink of CO_2 for 102–112 days (except for the rainfed maize field in 2003, likely because of severe moisture stress). The soybean fields, however, were a sink of CO_2 for a shorter time (78–86 days) before returning to a source of CO_2 in September to early October.

3.3.1. Growing season CO_2 exchange

3.3.1.1. Day and night time CO_2 exchange. Variations in daytime CO_2 exchange are primarily controlled by PAR (photosynthetically active radiation), LAI (green leaf area index), and soil water (e.g., Baldocchi, 1994, Rochette et al., 1996 and Suyker et al., 2004). For maize, peak CO_2 uptake was 64–68 μmol CO_2 m^{-2} s^{-1} in the irrigated fields and about 59 μmol CO_2 m^{-2} s^{-1} in the rainfed field (the corresponding LAIs were about 5.7 and 4.2, respectively). In contrast, peak CO_2 uptake for soybean was only 39 μmol CO_2 m^{-2} s^{-1} in the irrigated field (LAI ≈ 5.5) and 34 μmol CO_2 m^{-2} s^{-1} in the rainfed field (LAI ≈ 3.0). The peak CO_2 uptake we measured for maize is about 2–3 times the values reported for tallgrass prairies and temperate forests.

The night CO_2 emissions are primarily controlled by temperature, soil moisture, and LAI (e.g., Rochette et al., 1996 and Suyker et al., 2004). For maize, the peak CO_2 emission rates were 14–16 μmol CO_2 m^{-2} s^{-1} in the irrigated fields and 9–11 μmol CO_2 m^{-2} s^{-1} in the rainfed fields. Peak CO_2 emission rates for soybean were 16 μmol CO_2 m^{-2} s^{-1} in the irrigated field and 9 μmol CO_2 m^{-2} s^{-1} in the rainfed field. These peak night

Table 2. Mean values of air temperature (T_a, at 6 m), soil temperature (T_s, 0.1 m depth), incoming photosynthetically active radiation (PAR), precipitation, irrigation, soil volumetric water content (VWC, top 1 m) and peak green leaf area (LAI)

Year	Period	T_a (°C)	T_s (°C)	PAR ($\mu mol\ m^{-2}\ s^{-1}$)	Precipitation (mm)	Irrigation (mm)	VWC ($m^3\ m^{-3}$)	Peak LAI ($m^2\ m^{-2}$)
Site 1: irrigated continuous maize								
2001–2002	May–September	21.8	22.3	487	411	335	0.29	6.0
	October–February	4.1	5.0	215	122	0	0.27	–
	March–April	5.9	5.1	368	74	0	0.28	–
	Total	11.8	12.2	354	607	335	0.28	–
2002–2003	May–September	21.7	20.5	500	356	302	0.30	6.0
	October–February	0.6	2.9	205	109	0	0.29	–
	March–April	8.0	5.6	367	82	0	0.31	–
	Total	10.6	10.7	355	547	302	0.30	–
2003–2004	May–September	20.7	19.7	489	352	378	0.30	5.5
	October–February	1.1	3.8	202	99	0	0.30	–
	March–April	9.6	7.5	354	105	0	–	–
	Total	10.7	11.1	347	556	378	–	–
Site 2: irrigated maize–soybean rotation								
2001–2002	May–September	22.4	22.2	507	410	318	0.29	6.1
	October–February	3.9	4.7	217	127	0	0.29	–
	March–April	5.8	5.3	372	79	0	0.30	–
	Total	11.9	12.1	364	616	318	0.29	–
2002–2003	May–September	21.7	20.8	510	334	201	0.29	5.5
	October–February	0.5	3.0	208	108	0	0.29	–
	March–April	7.9	6.6	371	84	0	0.27	–
	Total	10.6	11.0	361	526	201	0.29	–
2003–2004	May–September	20.3	19.2	505	343	350	0.30	5.5
	October–February	1.0	3.5	208	106	0	0.30	–
	March–April	9.5	7.7	365	107	0	–	–
	Total	10.4	10.7	358	556	350	–	–
Site 3: rainfed maize–soybean rotation								
2001–2002	May–September	22.7	24.0	503	433	–	0.26	3.9
	October–February	4.0	4.6	221	115	–	0.26	–
	March–April	5.9	5.1	375	84	–	0.25	–
	Total	12.1	12.8	364	632	–	0.26	–
2002–2003	May–September	22.0	22.0	511	350	–	0.24	3.0
	October–February	0.5	2.8	214	112	–	0.26	–
	March–April	8.0	6.2	378	91	–	0.24	–
	Total	10.7	11.4	365	553	–	0.25	–
2003–2004	May–September	20.8	20.9	512	356	–	0.25	4.3
	October–February	1.0	3.4	217	110	–	0.26	–
	March–April	9.6	7.9	380	115	–	–	–
	Total	10.7	11.5	367	581	–	–	–

Measurements in 2001 started on May 25 at Site 1, June 7 at Site 2, and June 13 at Site 3. Data from a nearby automated weather station were used to fill in the missing values.

emission rates in maize and soybeans are comparable to the values observed in a tallgrass prairie, but about twice the values observed in temperate forests.

3.3.1.2. Seasonally integrated CO_2 exchange. Values of GPP, R_e, and NEP for the maize–soybean systems over the growing season are compared in Figure 2. Two significant features of maize and soybean

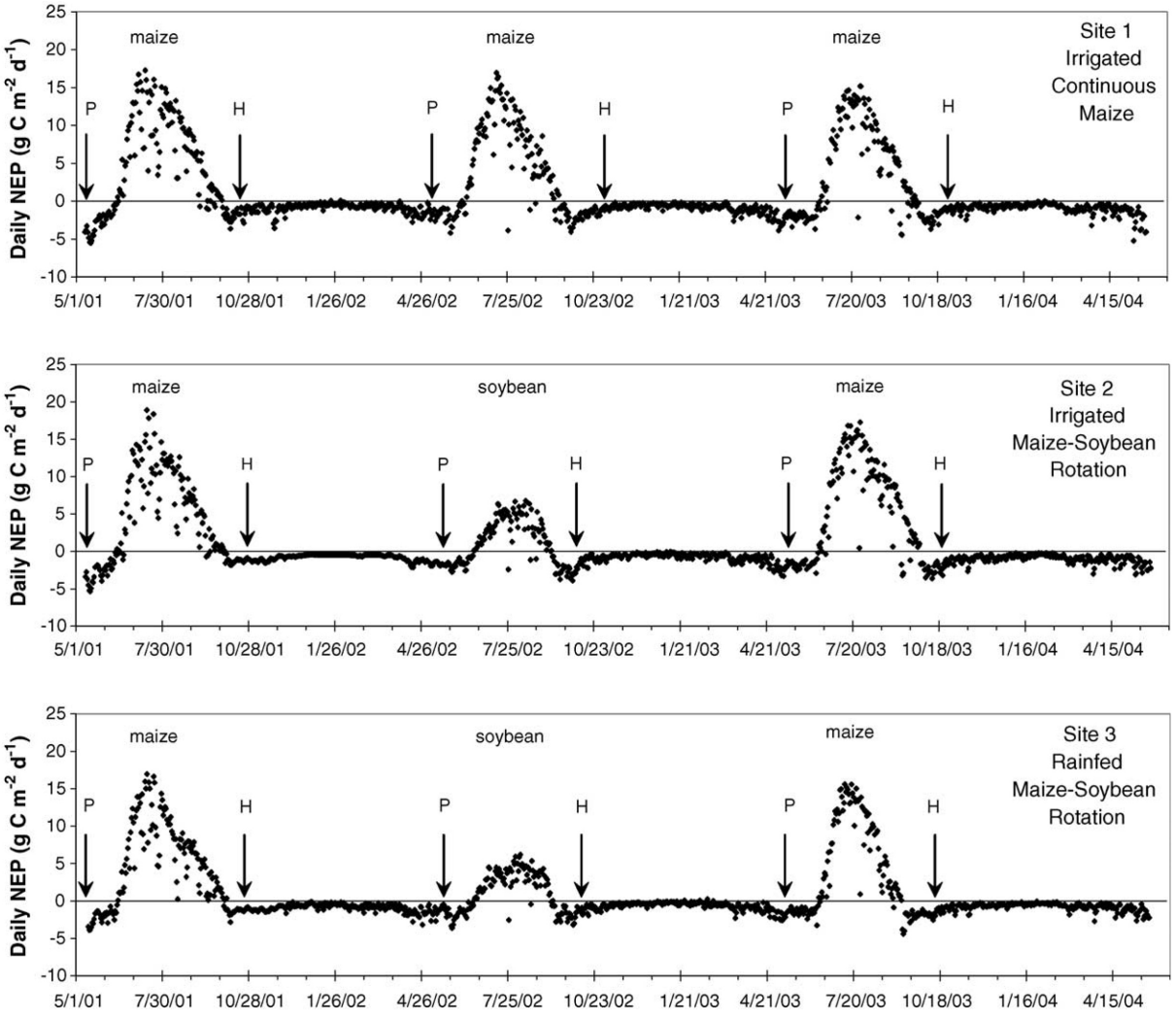

Figure 1. Daily values of net ecosystem production (NEP) at the three study sites for 3 years. Dates of planting (P) and harvest (H) are also indicated.

CO_2 exchange emerge: (a) maize, both irrigated and rainfed, has a much larger GPP (by 80%, Figure 2) and (b) the R_e/GPP ratio for soybean (0.80–0.85) is higher than in maize (0.55–0.65). C input to soil from previous crop residues likely had an effect on the R_e/GPP ratio of soybean. Consequently, the seasonally integrated NEP in both irrigated and rainfed maize is substantially larger (ca. 4:1 ratio) than soybean.

Compared to rainfed maize in 2001, the seasonally integrated GPP in irrigated maize was larger by about 230 g C m^{-2} (Figure 2B). The R_e was also larger in the irrigated maize by a similar amount (≈225 g C m^{-2}). Similar differences in GPP and R_e for irrigated and rainfed maize were observed in 2003. The additional moisture in the irrigated field resulted in greater ecosystem respiration, thereby offsetting the advantage in GPP to give about the same NEP for the rainfed and irrigated maize fields. A comparison of the results from the irrigated and rainfed soybean fields reveals a similar situation, indicating that, during the growing season, an increase in ecosystem respiration in irrigated soybean compensated for the increase in GPP, thus resulting in about the same NEP values as in rainfed soybean (Figure 2C).

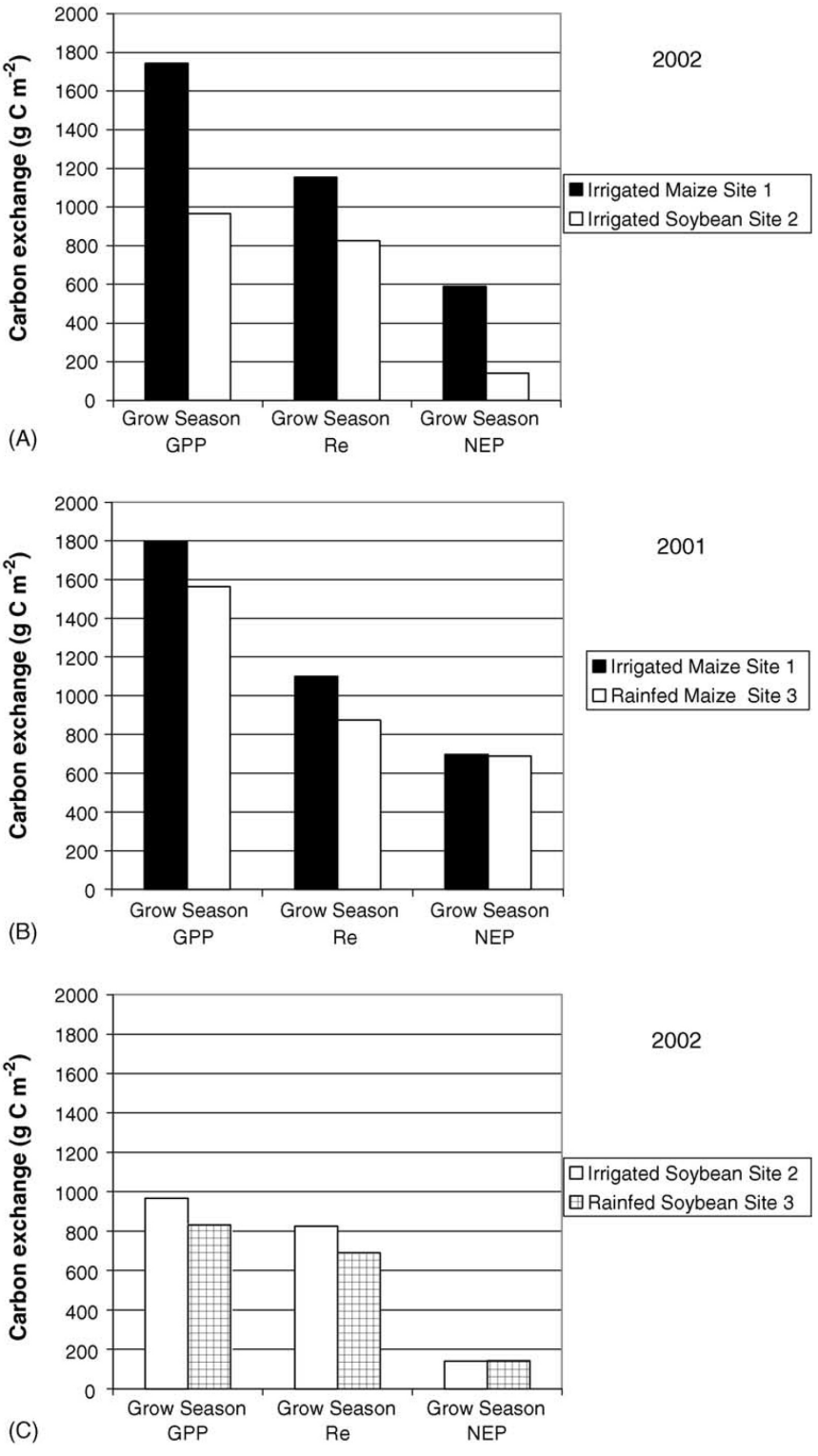

Figure 2. Comparison of integrated magnitudes of gross primary productivity (GPP), ecosystem respiration (R_e), and net ecosystem production (NEP) over the growing season: (A) irrigated maize and soybean; (B) irrigated and rainfed maize; (C) irrigated and rainfed soybean.

3.3.1.3. NEP–biomass relationship. Following Biscoe et al. (1975), we calculated the daily net gain of CO_2 by the crop as follows:

$$\text{daily net gain of } CO_2 \text{ by the crop} = \text{daily NEP} + \text{daily } R_h \quad (3)$$

where R_h is the heterotrophic component of total soil respiration (F_s). A comparison of the cumulative daily crop C gain (Eq. (3): from planting to physiological maturity, determined from the measured NEP and estimated R_h), and the total (above and belowground) biomass-C at physiological maturity for the three sites in each of the 3 years is shown in Figure 3. Values of cumulative daily crop C gain lie within ±15% of measured total plant biomass. Such an analysis is dependent on a number of assumptions. Our measurement of root-excluded versus non-root excluded F_s to estimate R_h assumes that basal heterotrophic respiration of CO_2 from SOC in non-root excluded soil (R_h) is the same as that in root excluded soil and is not influenced by microbial population shifts that might occur from root C inputs (exudates and root turnover). If this assumption is wrong, it would result in an overestimation of plant root respiration (*underestimation of* R_h). On the other hand, some plant C (non-respired photosynthesis) is lost as root exudates and root turnover which is likely to be rapidly metabolized and respired by the heterotrophic soil population. Studies have shown that approximately 30% of total maize belowground C allocation can occur as rhizosphere deposition (i.e., exudation and fine root turnover) (Haller and Stolp, 1985 and Qian et al., 1997). Failure to account for root exudate contributions to F_s would result in an overestimation of R_h. In view of the uncertainties involved in measuring and estimating the variables involved, the comparison shown in Figure 3 seems reasonable.

3.3.2. Non-growing season (autumn/winter/spring) CO_2 exchange. Highest ecosystem respiration (R_e) rates during the non-growing season (about 4.5 μmol CO_2 m^{-2} s^{-1}) were observed near harvest time, probably due to warm temperatures in October and the large amount of senescent crop biomass. Similarly large R_e values were observed during warmest days in the spring. During the coldest periods of January to February, R_e was very small. Daily R_e was found to be correlated with soil temperature at all depths, with closest correlation to the soil temperature at 0.06, 0.10, and 0.20 m depths (R^2 = 0.59–0.71, $P < 0.01$). Statistically significant correlation was not observed with soil moisture. Magnitudes of R_e, integrated over the non-growing season, ranged from 170 to 255 g C m^{-2}. The non-growing season R_e was about 0.15–0.25 of the R_e during the growing season.

3.3.3. Annually integrated CO_2 exchange. On an annual basis, the GPP in irrigated maize ranged from 1600 to 1800 g C m^{-2} (Figure 4: the annual integration started at the time of planting). Of these amounts, about 65–75% was emitted as R_e, thus the annual NEP ranged from 380 to 570 g C m^{-2}. In years 2 and 3, the annual NEP of the irrigated continuous maize declined by 18 and 26%, as compared to 2001 (the grain yield also declined by 5 and 11%, respectively). Reduced NEP in 2002 and 2003 was likely caused by constraints associated with the large amount of crop residues that accumulate in this high-yield, no-till system. Such constraints include difficulties in sowing and in obtaining uniform stand establishment, and carryover pest problems from western corn rootworm infestation (*Diabrotica virgifera virgifera* LeConte) and grey leaf spot fungal disease (*Cercospora zeae-maydis* Tehon & Daniels). In rainfed maize in year 1, both the GPP and R_e were reduced by similar amounts due to both lower planting density and short-term water deficits compared to irrigated maize. Therefore, the annual NEP was about the same in both rainfed and irrigated maize (510 g C m^{-2}). The smaller NEP (400 g C m^{-2}) at the rainfed maize site in year 3 was due to periods of severe water deficit experienced during some of the growing season.

The annual NEP values of 300–500 g C m^{-2} in these high-yield maize systems (Figure 4) were much greater than those observed at forest sites in USA [Harvard forest, MA: 200 g C m^{-2} (Barford et al., 2003); Howland forest, MA: 174 g C m^{-2} (Hollinger et al., 2004); University of Michigan Biological Station: 80–170 g C m^{-2} (Schmid et al., 2003); Wind River Canopy Crane Research Facility, WA: −50 to 200 g C m^{-2} (M. Falk, 26th American Meteorological Society Conference on Agricultural and Forest Meteorology, Vancouver, BC, Canada, personal communications)]. In contrast, annual NEP

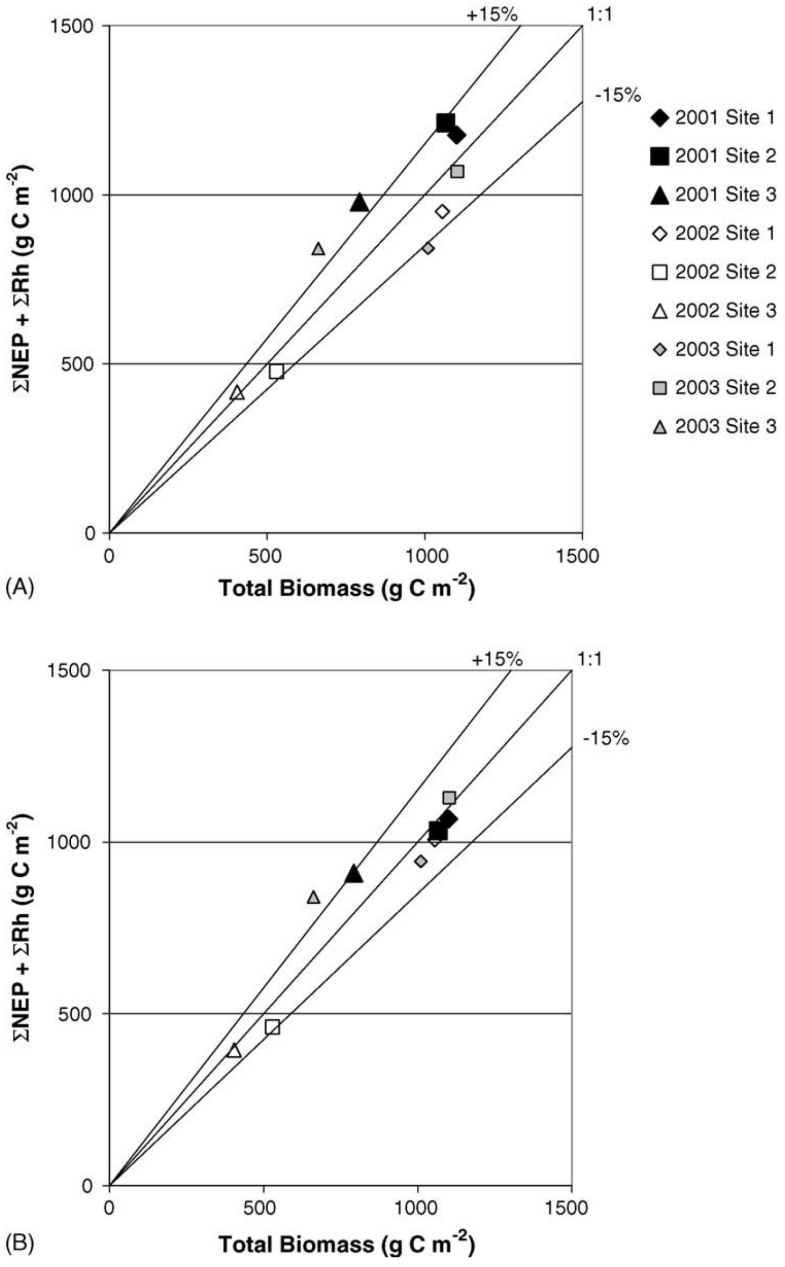

Figure 3. Comparison of cumulative net ecosystem production (NEP) + cumulative heterotrophic respiration (R_h) vs. total biomass, accumulated between planting and physiological maturity at the three sites in 3 years: (A) R_h estimated from chambers; (B) R_h estimated from night CO_2 exchange (see text for details).

values for secondary growth Douglas fir on the Canadian West Coast range from 270 to 420 g C m^{-2} (Morgenstern et al., 2004), which approach those of maize in our study. Studies in native grasslands have reported annual NEP values ranging from 50 to 275 g C m^{-2} (tallgrass prairie, OK: Suyker et al., 2003), −18 to 20 g C m^{-2} (northern temperate grassland in Alberta, Canada: Flanagan et al., 2002), and −30 to 130 g C m^{-2} (Mediterranean, annual grassland: Xu and Baldocchi, 2003), which are considerably smaller than for maize in our study.

The annual GPP of soybean was only 45–55% of maize GPP with or without irrigation. The annual soybean R_e, however, was about 3–5% larger

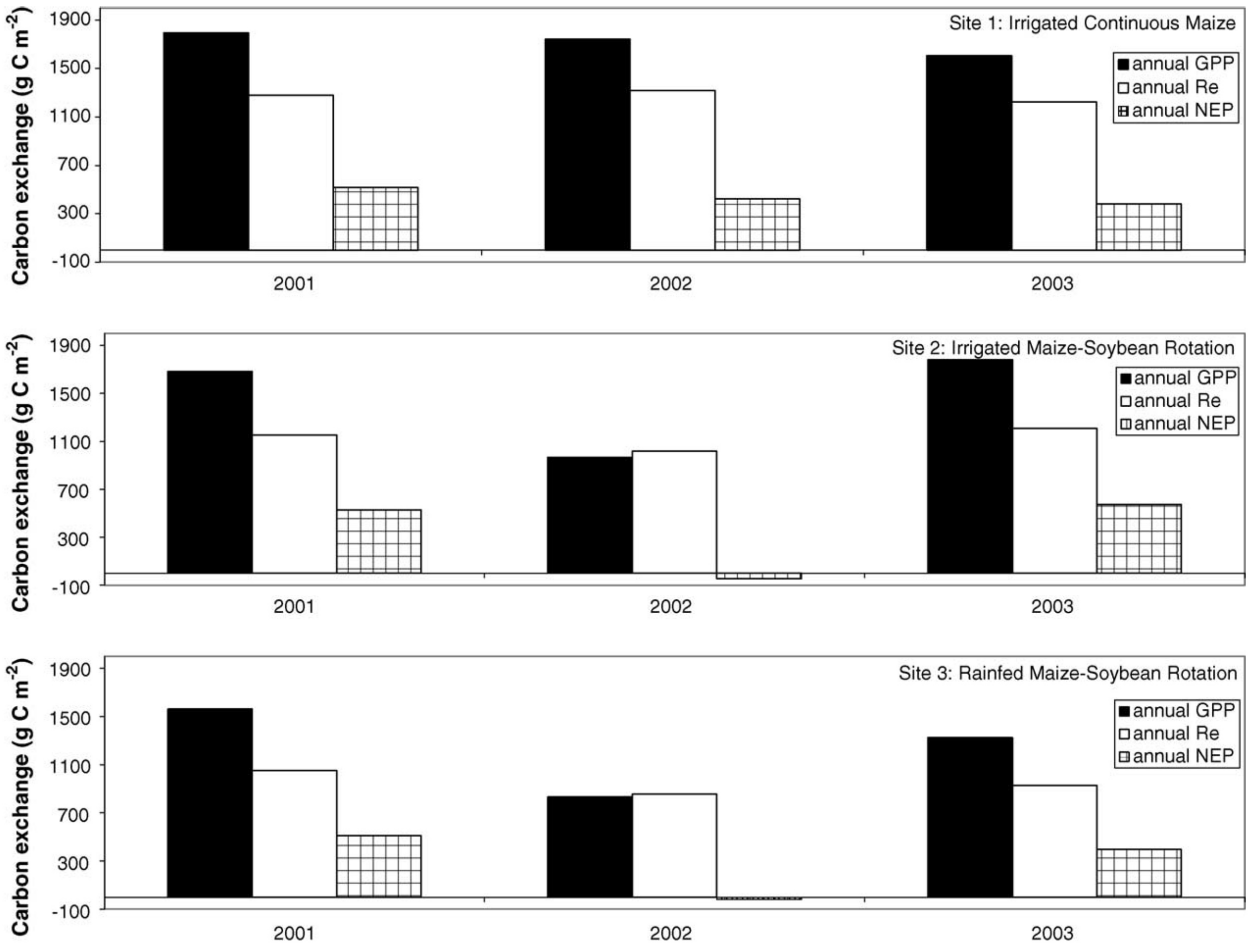

Figure 4. Annual magnitudes of gross primary productivity (GPP), ecosystem respiration (R_e), and net ecosystem production (NEP) for the three study sites in 3 years. Annual integration began at the time of planting.

than its GPP, which resulted in an annual NEP in the soybean fields that ranged from −20 to −45 g C m^{-2}.

3.4. Carbon balance

3.4.1. Tower eddy covariance measurements. In considering the annual C balance of an agricultural system as estimated from NEP, the grain C removed with grain harvest must be considered. Our assumption here is that C exported in grain harvest has a relatively short half-life and does not contribute to long-term C sequestration. For irrigated fields, the CO_2 released from irrigation (obtained from groundwater) needs to be considered. In a manner similar to that used by Anthoni et al. (2004), we calculated the net biome production (NBP) of the ecosystem as:

$$\text{NBP} = \text{annual NEP} - C_g + I_c \quad (4)$$

where C_g is the amount of C removed with harvested grain and I_c is the CO_2 released from irrigation water. The estimates of I_c in our study ranged from 26 to 49 g C m^{-2} $year^{-1}$. Schlesinger (1999) estimated a lower value (8 g C m^{-2} $year^{-1}$), based on a hypothetical irrigated system with 1.25 mM Ca (2.5 mM bicarbonate) in the applied irrigation but did not account for release of dissolved CO_2 in water. The irrigation water collected at the wellhead of Site 1 in our study contained 4.2 mM bicarbonate, and our direct measurement would also have included the release of dissolved CO_2 in the sample

(Reid et al., 1987). Our estimates of I_c are based on in vitro direct measurements of CO_2 release from irrigation water applied to soil, corrected for microbial respiration, and the actual amount of water applied by irrigation to each cropping system. During certain conditions (e.g., night time irrigation during low winds, shifts in wind direction) CO_2, which is quickly released from the irrigation water, may not be sensed by the tower eddy covariance sensors. So for the irrigated sites, a range of values for NBP is given in Table 3 to include two likely possibilities: (a) 75% of the CO_2 released from the irrigation water was transported to the atmosphere without being sensed by the tower eddy covariance sensors and (b) 25% of the CO_2 released from the irrigation water was transported to the atmosphere without being sensed by the tower eddy covariance sensors. This range recognizes the fact that, depending on the meteorological conditions during the circular movement of the sprinkler systems, the flux tower may not sense all of the CO_2 emission from the irrigation water, but also that it is unlikely that none of the CO_2 emitted is sensed.

Rainfed maize (Site 3, years 1 and 3) was a C sink with a NBP of 100–175 g C m^{-2} $year^{-1}$ (Table 3, top half). The NBP of irrigated maize (Site 1: all years; Site 2: years 1 and 3) varied from −77 to 68 g C m^{-2} $year^{-1}$. Both the rainfed and irrigated soybean fields (year 2) were a significant source of C with a NBP of −171 to −225 g C m^{-2} $year^{-1}$,

Table 3. Annual carbon budget (g C m^{-2}) using tower eddy covariance measurements

A.

Site 1: irrigated continuous maize (2003–2004),	Year 1 (2001–2002), maize	Year 2 (2002–2003), maize	Year 3 maize
Annual NEP	517	424	381
Grain C removal during harvest (C_g)	521	503	470
Estimated CO_2 release from irrigation water (I_c)	43	39	49
NBP	7–28	−69 to −50	−77 to −52
Site 2: irrigated maize–soybean rotation (2003–2004),	**Year 1 (2001–2002), maize**	**Year 2 (2002–2003), soybean**	**Year 3 maize**
Annual NEP	529	−48	572
Grain C removal during harvest (C_g)	518	183	538
Estimated CO_2 release from irrigation water (I_c)	41	26	45
NBP	21–42	−225 to −212	45–68
Site 3: rainfed maize–soybean rotation (2003–2004),	**Year 1 (2001–2002), maize**	**Year 2 (2002–2003), soybean**	**Year 3 maize**
Annual NEP	510	−18	397
Grain C removal during harvest (C_g)	335	153	297
NBP	175	−171	100

B.

Agroecosystem	**NBP**
Irrigated continuous maize (Site 1)	−46 to −25 (3 year average)
Irrigated maize–soybean rotation (Site 2)	−102 to −85 (years 1 and 2 average); −90 to −72 (years 2 and 3 average)
Rainfed maize–soybean rotation (Site 3)	+2 (years 1 and 2 average); −36 (years 2 and 3 average)

The two values included in net biome production (NBP = annual NEP − C_g + I_c) for the irrigated sites represent a range of likely possibilities: (a) 75% of the CO_2 released from the irrigation water was transported to the atmosphere without being sensed by the tower eddy covariance sensors or (b) 25% of the CO_2 released from the irrigation water was transported to the atmosphere without being sensed by the tower eddy covariance sensors. This range recognizes the fact that, depending on the meteorological conditions during the circular movement of the sprinkler systems, the tower sensors may not sense all of the CO_2 emitted from the applied irrigation water, and that it is unlikely that none of the CO_2 emitted is sensed.

respectively. Examination of these cropping systems over the first 3-year study period (Table 3, bottom half) indicates that the rainfed maize–soybean rotation system is approximately C neutral, given the uncertainties (±45 g C m^{-2}, approximately) associated with these estimates. Our results for rainfed maize–soybean are comparable to the results from ongoing studies on rainfed maize–soybean rotation in Illinois and Minnesota (T. Meyers and J. Baker, 26th American Meteorological Society Conference on Agricultural and Forest Meteorology, Vancouver, BC, Canada, personal communications). The NBP for the irrigated continuous maize (Table 3, bottom half) indicates that this system is nearly C neutral or a slight source of C. The irrigated maize–soybean rotation, on the other hand, appears to be a moderate source of C.

3.4.2. Crop residue decomposition and soil carbon stocks. Measurement of litter mass over time showed that the rate of decomposition (i.e., C loss) from maize residues was similar in both irrigated and rainfed sites (half life, $t_{1/2}$ ~ 1.39 year) (Figure 5). The $t_{1/2}$ of soybean residue decomposition (1.25 and 1.06 year for irrigated and rainfed, respectively) indicated soybean decomposed 10–24% faster than maize residue.

Changes in the size of the litter-C pool were estimated based on the measured amount of crop residues added to the surface litter layer in each field after grain harvest, the litter degradation rates from Figure 5, and an estimate of the amount of surface litter incorporated in soil when the fields were disked to initiate our study. Estimates of the litter-C pool using this approach indicate that the size of this C pool has increased by 143 g C m^{-2} from May 2001 to May 2002, an additional 72 g C m^{-2} from May 2002 to May 2003, and by another 14 g C m^{-2} from May 2003 to May 2004 in continuous, irrigated maize. Litter-C pools in this system have increased because of the high yields and corresponding high litter inputs achieved in our study. Within the irrigated maize–soybean rotation, litter-C pools are strongly dependent on whether the current year is cropped to soybean or maize. The litter-C pool increased by 161 g C m^{-2} from May 2001 to May 2002 (a maize year), decreased by 100 g C m^{-2} from May 2002 to May 2003 (a soybean year), and increased again by 144 g C m^{-2} from May 2003 to May 2004 (a maize year). Thus, much of the C gain in a maize year is offset by C loss during the alternating soybean year. It was not possible to estimate the changes in the litter-C pool in the rainfed maize–soybean rotation because the field was not managed uniformly before initiating the current study.

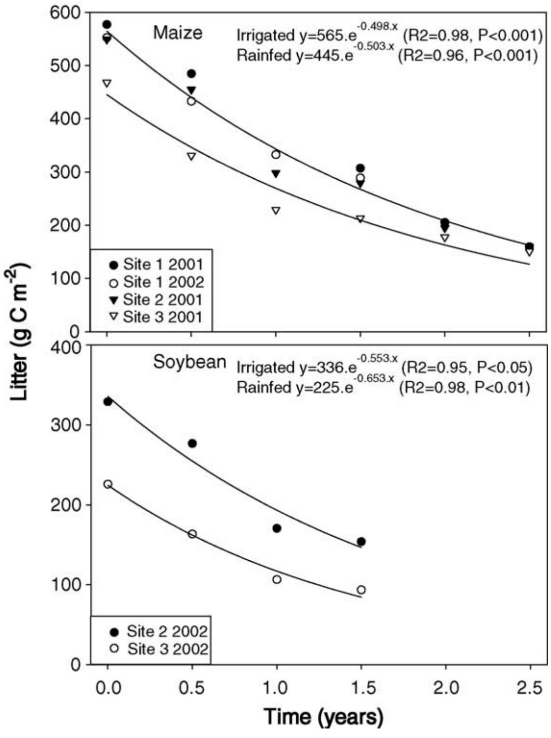

Figure 5. Estimated whole-field carbon loss from measurements of litter decomposition in litterbags. Initial litter carbon was determined in crop residue samples of above and belowground organs collected at harvest. The best-fit regression is an exponential decay and these regressions did not differ significantly for irrigated maize across fields and years such that the irrigated maize data were pooled in combined regression.

In all three cropping systems, mean SOC changes from 2001 to 2004 ranged from −80 to −129 g C m^{-2} for the top 200 kg of soil m^{-2} (approximately 0–0.15 m depth), suggesting some loss of SOC may have occurred from the topsoil layer. However, weighted standard errors for C stock measurement in this soil mass were in the 130–150 g C m^{-2} range at Sites 1 and 2 and 230–250 g C m^{-2} at Site 3 (Figure 6). Similarly, small but non-significant decreases in mean SOC were measured for the top 400 kg of soil m^{-2} (−4 to −51 g C m^{-2}), which roughly corresponds to the 0–0.30 m depth. These

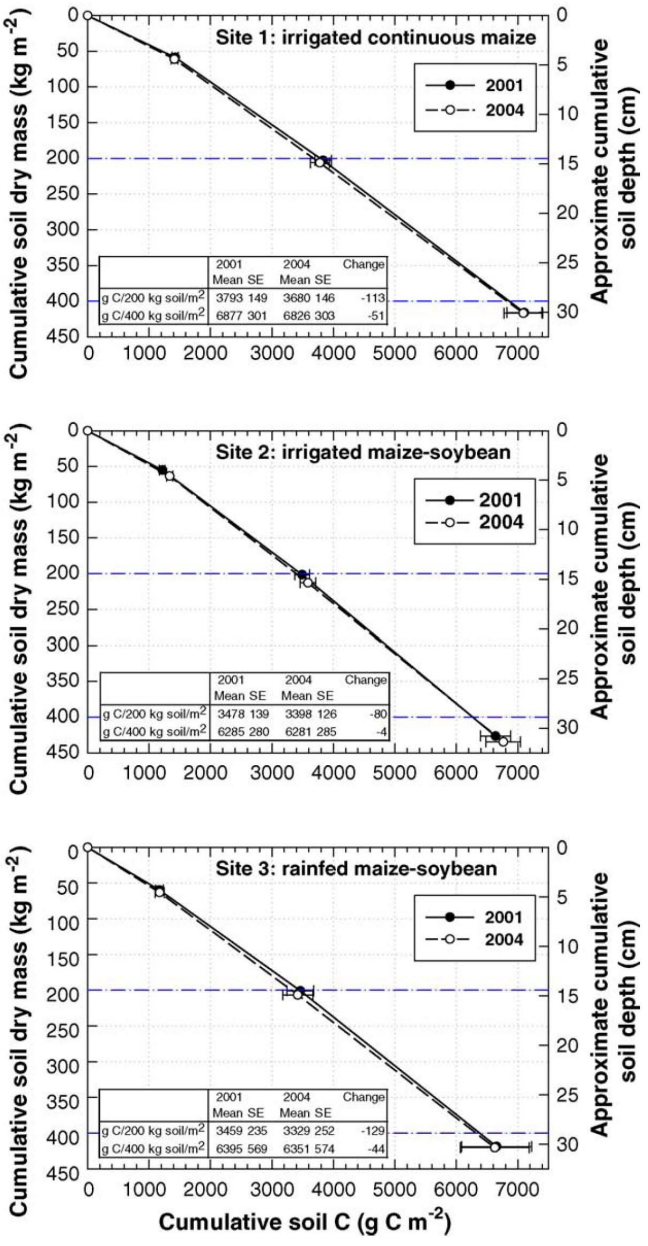

Figure 6. Cumulative soil C contents in spring 2001 and 2004 as a function of cumulative soil dry mass. Values shown are spatially weighted site means and standard errors. The dashed horizontal lines indicate the top 200 kg dry soil m^{-2} and 400 kg dry soil m^{-2} (oven-dry basis) used as reference soil mass for monitoring changes in soil organic carbon.

values compare with weighted standard errors that ranged from 280 to 570 g C m^{-2} for this depth interval. In summary, given the attainable precision of these estimates, we conclude that there was no detectable change in soil C stock during the first 3 years of no-till farming in the three cropping systems in our study.

3.4.3. Comparison with other studies in agroecosystems. As mentioned before, our results from the rainfed maize–soybean rotation system during the first 3 years indicate a lack of C sequestration and are consistent with the results of ongoing studies in Minnesota and Illinois. Our results, however, differ from those from some

studies, probably due to differences in cropping systems and management, as well as to differences in methods used to measure changes in SOC over time. In a summary of long-term experiments, West and Post (2002) suggested an average annual C sequestration rate of 44 g C m^{-2} for continuous maize systems and 90 g C m^{-2} for maize–soybean rotations, mostly under rainfed conditions. These values were calculated as the *relative difference* in SOC between no-till and conventional tillage treatments in long-term experiments at one point in time after periods of 10–20 years. Moreover, direct measurements of SOC and soil bulk density were not available in most experiments evaluated by West and Post (2002) so that C stocks were not comparable on an equivalent soil mass basis. Relatively small differences in soil bulk density between treatments, or over time in the same treatment, can result in errors of 5–15% in estimating SOC stocks (Gifford and Roderick, 2003).

Six et al. (2004) also analyzed published data from numerous long-term experiments in North America and other parts of the world, again without correction for possible changes in bulk density. They concluded that average C sequestration rates in the first few years after conversion from conventional tillage to no-till were small or sometimes negative, followed by a gradual increase over time. Averaged over the published studies summarized in their report, C sequestration rates in humid climates averaged 22 g C m^{-2} $year^{-1}$ in the top 0.30 m of soil over a 20-year period, and 10 g C m^{-2} $year^{-1}$ in dry climates. Our SOC measurements confirm a lack of soil C sequestration or possibly even losses of SOC (Figure 6) in 3 years of no-till management following an initial disking operation. These findings are consistent with the supposition that movement of carbon from the decomposition of crop residue litter on the soil surface into the deeper soil profile is a relatively slow process under no-till conditions. In contrast, root-derived C is likely the primary source for replenishing SOC lost to heterotrophic respiration during the initial years after conversion to no-till (Gale and Cambardella, 2000). In quantitative terms, however, the total amount of root-derived C is small relative to surface litter residue as well as relative to the annual loss of SOC from mineralization.

4. Summary and concluding remarks

Results from 3 years of CO_2 exchange measurements are presented for three production-scale fields, each with a different maize-based cropping system: (a) irrigated continuous maize, (b) irrigated maize–soybean rotation, and (c) rainfed maize–soybean rotation. All fields were initially tilled by disking to create uniform starting conditions. Since then, all fields have been under no-till management. Progressive crop management was used to achieve crop yields and N fertilizer efficiencies that were substantially greater than average yield and efficiency achieved by most farmers. Cumulative daily crop C gain, calculated from integrated net ecosystem production (NEP) from sowing to physiological maturity, compared well with direct measurement of total plant biomass. Maize fields were a C sink for about 20 days longer than soybean fields (100–110 days versus 80–85 days). Peak hourly daytime CO_2 uptake in maize was significantly larger than in soybean (59–68 μmol CO_2 m^{-2} s^{-1} versus 34–39 μmol CO_2 m^{-2} s^{-1}). In a growing season, the NEP for maize was substantially larger than for soybean due to a larger gross primary productivity (GPP) and a proportionately smaller ecosystem respiration. The large C input from crop residues on the soil surface and roots of the previous maize crop contributed to a higher R_e during the soybean phase of the crop rotation and a higher R_e/GPP ratio for soybean. Compared to the rainfed system, increased ecosystem respiration caused by higher soil moisture levels in irrigated maize and soybean fields offset the advantage of greater GPP in the calculation of NEP. The grain-C removed with harvest and the CO_2 released from irrigation were combined with the annual NEP values to estimate net biome C production. After 3 years of cropping under the conditions of this study, such calculations indicate that the rainfed maize–soybean rotation is nearly C neutral, the irrigated continuous maize system is nearly C neutral or a slight source of C and the irrigated maize–soybean rotation system is a moderate source of C. Likewise, a statistically significant change in soil C stocks could not be detected in the three cropping systems during the 3-year period of this study. The litter-C pools (including roots, stalks, leaves, and cobs) were estimated to increase in the irrigated continuous maize and in the irrigated maize–soy-

bean rotation (by 230 and 200 g C m^{-2} $year^{-1}$, respectively) over the 3-year period, and the future soil C balance in these systems will depend on the fate of C in these accumulating litter pools.

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References

Anthoni et al., 2004: P.M. Anthoni, A. Freibauer, O. Kolle and E.D. Schulze, Winter wheat carbon exchange in Thuringia, Germany, *Agric. For. Meteorol.* **121** (2004), pp. 55–67.

Baldocchi et al., 1988: D.D. Baldocchi, B.B. Hicks and T.P. Meyers, Measuring biosphere–atmosphere exchanges of biologically related gases with micrometeorological methods, *Ecology* **69** (1988) (5), pp. 1331–1340.

Baldocchi, 1994: D.D. Baldocchi, A comparative study of mass and energy exchange rates over a closed C_3 (wheat) and an open C_4 (corn) crop. II. CO_2 exchange and water use efficiency, *Agric. For. Meteorol.* **67** (1994), pp. 291–321.

Baldocchi et al., 1997: D.D. Baldocchi, C. Vogel and B. Hall, Seasonal variation of carbon dioxide exchange rates above and below a boreal jack pine forest, *Agric. For. Meteorol.* **83** (1997), pp. 147–170.

Barford et al., 2003: C.C. Barford, S.C. Wofsy, M.L. Goulden, J.W. Munger, P.E. Hammond, S.P. Urbanski, L. Hutyra, S.R. Saleska, D. Fitzjarrald and K. Moore, Factors controlling long- and short-term sequestration of atmospheric CO_2 in a mid-latitude forest, *Science* **294** (2003), pp. 1688–1691.

Biscoe et al., 1975: P.V. Biscoe, R.K. Scott and J.L. Monteith, Barley and its environment. III. Carbon budget of the stand, *J. Appl. Ecol.* **12** (1975), pp. 269–291.

Burgess et al., 2002: M.S. Burgess, G.R. Mehuys and C.A. Madramootoo, Decomposition of grain-corn residues (*Zea mays* L.): a litterbag study under three tillage systems, *Can. J. Soil Sci.* **82** (2002) (2), pp. 127–138.

Caldeira et al., 2004: K. Caldeira, M.G. Morgan, D. Baldocchi, P.G. Brewer, C.T.A. Chen, G.J. Nabuurs, N. Nakicenovic and G.P. Robertson, A portfolio of carbon management options. In: C.B. Field and M.R. Raupach, Editors, *The Global Carbon Cycle*, Island Press, Washington, DC, USA (2004), pp. 103–109.

Cassman et al., 2002: K.G. Cassman, A. Dobermann and D.T. Walters, Agroecosystems, nitrogen-use efficiency, and nitrogen management, *Ambio* **31** (2002), pp. 132–140.

Cassman et al., 2003: K.G. Cassman, A. Dobermann, D.T. Walters and H.S. Yang, Meeting cereal demand while protecting natural resources and improving environmental quality, *Ann. Rev. Environ. Res.* **28** (2003), pp. 315–358.

Flanagan et al., 2002: L.B. Flanagan, L.A. Wever and P.J. Carlson, Seasonal and interannual variation in carbon dioxide exchange and carbon balance in a northern temperate grassland, *Global Change Biol.* **8** (2002), pp. 599–615.

Gale and Cambardella, 2000: W.J. Gale and C.A. Cambardella, Carbon dynamics of surface residue- and root-derived organic matter under simulated no-till, *Soil Sci. Soc. Am. J.* **64** (2000), pp. 190–195.

Gifford and Roderick, 2003: R.M. Gifford and M.L. Roderick, Soil carbon stocks and bulk density: spatial or cumulative mass coordinates as a basis of expression?, *Global Change Biol.* **9** (2003), pp. 1507–1514.

Haller and Stolp, 1985: T. Haller and H. Stolp, Quantitative estimation of root exudation of maize plants, *Plant Soil* **86** (1985), pp. 207–216.

Hollinger et al., 2004: D.Y. Hollinger, J. Aber, B. Dail, E.A. Davidson, S.M. Goltz, H. Hughes, M.Y. Leclerc, J.T. Lee, A.D. Richardson, C. Rodrigues, N.A. Scott, D. Achuatavarier and J. Walsh, Spatial and temporal variability in forest-atmosphere CO_2 exchange, *Global Change Biol.* **10** (2004), pp. 1689–1706.

Houghton et al., 1983: R.A. Houghton, J.E. Hobbie, J.M. Melillo, B. Moore, B.J. Peterson, G.R. Shaver and G.M. Woodwell, Changes in the carbon content of the terrestrial biota and soils between 1860 and 1980: a net release of CO_2 to the atmosphere, *Ecol. Mono.* **53** (1983), pp. 235–262.

Hutchinson and Mosier, 1981: G.L. Hutchinson and A.R. Mosier, Improved soil cover method for field measurement of nitrous oxide fluxes, *Soil Sci. Soc. Am. J.* **45** (1981), pp. 311–316.

IPCC, 2000: IPCC, 2000. Land use, land-use change, and forestry. Special report of the IPCC. Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge.

Kim et al., 1992: J. Kim, S.B. Verma and R.J. Clement, Carbon dioxide budget in a temperate grassland ecosystem, *J. Geophys. Res.* **97** (1992) (D5), pp. 6057–6063.

Lal et al., 2003: R. Lal, R.F. Follett and J.M. Kimble, Achieving soil carbon sequestration in the United States: a challenge to the policy makers, *Soil Sci.* **168** (2003), pp. 827–845.

Law et al., 2002: B.E. Law, E. Falge, L. Gu, D.D. Baldocchi, P. Bakwin, P. Berbigier, K. Davis, A.J. Dolman, M. Falk, J.D. Fuentes, A. Goldstein, A. Granier, A. Grelle, D. Hollinger, I.A. Janssens, P. Jarvis, N.O. Jensen, G. Katul, Y.

Mahli, G. Matteucci, T. Meyers, R. Monson, W. Munger, W. Oechel, R. Olson, K. Pilegaard, K.T. Paw, U.H. Thorgeirsson, R. Valentini, S. Verma, T. Vesala, K. Wilson and S. Wofsy, Environmental controls over carbon dioxide and water vapor exchange of terrestrial vegetation, *Agric. For. Meteorol.* **113** (2002), pp. 97–120.

Massman, 1991: W.J. Massman, The attenuation of concentration fluctuations in turbulent flow in a tube, *J. Geophys. Res.* **96** (1991), pp. 15269–15273.

Meyers and Hollinger, 2004: T.P. Meyers and S.E. Hollinger, An assessment of storage terms in the surface energy balance of maize and soybean, *Agric. For. Meteorol.* **125** (2004), pp. 105–116.

Minasny and McBratney, 2003: Minasny, B., McBratney, A.B., 2003. FuzME, Version 3.0. Australian Centre for Precision Agriculture, The University of Sydney, Sydney, Accessed June 10, 2004, http://www.usyd.edu.au/su/agric/acpa .

Moore, 1986: C.J. Moore, Frequency response correction for eddy correlation systems, *Boundary-Layer Meteorol.* **37** (1986), pp. 17–35.

Morgenstern et al., 2004: K. Morgenstern, T.A. Black, E.R. Humphreys, T.J. Griffis, G.B. Drewitt, T. Cai, Z. Nesic, D.L. Spittlehouse and N.J. Livingston, Sensitivity and uncertainty of the carbon balance of a Pacific Northwest Douglas-fir forest during an El Niño/La Niña cycle, *Agric. For. Meteorol.* **123** (2004), pp. 201–219.

Norman et al., 1992: J.M. Norman, R. Garcia and S.B. Verma, Soil surface CO_2 fluxes and the carbon budget of a grassland, *J. Geophys. Res.* **97** (1992) (D17), pp. 18845–18853.

Paulus et al., 1999: R. Paulus, J. Roembke, A. Ruf and L. Beck, A comparison of the litterbag, minicontainer, and bait lamina methods in an ecotoxicological field experiment with Diflubenzuron and Btk, *Pedobiologia* **43** (1999), pp. 120–133.

Paustian et al., 1997: K. Paustian, O. Andren, H.H. Janzen, R. Lal, P. Smith, G. Tian, H. Tiessen, M. van Noordwijk and P. Woomer, Agricultural soils as sink to mitigate CO_2 emissions, *Soil Use Manage.* **13** (1997), pp. 230–244.

Qian et al., 1997: J.H. Qian, J.W. Doran and D.T. Walters, Maize plant contributions to root zone available carbon and microbial transformations of nitrogen, *Soil Biol. Biochem.* **29** (1997), pp. 1451–1462.

Reid et al., 1987: R.C. Reid, J.M. Prausnitz and B.E. Poling, The Properties of Gases and Liquids (4th ed.), McGraw-Hill, Boston (1987).

Robertson and Paul, 2000: G.P. Robertson and E.A. Paul, Decomposition and soil organic matter dynamics. In: O.E. Sala, R.B. Jackson, H.A. Mooney and R.W. Howart, Editors, *Methods in Ecosystem Science*, Springer Verlag, New York (2000), pp. 104–116.

Rochette et al., 1996: P. Rochette, R.L. Desjardin, E. Pattey and R. Lessard, Instantaneous measurement of radiation and water use efficiencies of a maize crop, *Agron. J.* **88** (1996) (4), pp. 627–635.

Schlesinger, 1986: W.H. Schlesinger, Changes in soil carbon storage and associated properties with disturbance and recovery. In: J.R. Trabalka and D.E. Reichle, Editors, *The Changing Carbon Cycle: A Global Analysis*, Springer Verlag, New York (1986), pp. 194–220.

Schlesinger, 1999: W.H. Schlesinger, Carbon sequestration in soils, *Science* **284** (1999), p. 2095.

Schmid et al., 2003: H.P. Schmid, H.-B. Su, C.S. Vogel and P.S. Curtis, Ecosystem–atmosphere exchange of carbon dioxide over a mixed hardwood forest in northern lower Michigan, *J. Geophys. Res.* **108** (2003) (D14), p. 4417.

Shapiro et al., 2001: C.A. Shapiro, R.B. Ferguson, G.W. Hergert, A. Dobermann and C.S. Wortmann, Fertilizer suggestions for corn. NebGuide G74-174-A. Cooperative Extension, Institute of Agriculture and Natural Resources, University of Nebraska–Lincoln, Lincoln, NE (2001).

Simbahan, 2004: Simbahan, G.C., 2004. Processing of spatial information for mapping of soil organic carbon. PhD dissertation. University of Nebraska–Lincoln, Lincoln, NE.

Six et al., 2004: J. Six, S.M. Ogle, F.J. Breidt, R.T. Conant, A.R. Mosier and K. Paustian, The potential to mitigate global warming with no-tillage management is only realized when practiced in the long term, *Global Change Biol.* **10** (2004), pp. 155–160.

Suyker and Verma, 1993: A.E. Suyker and S.B. Verma, Eddy correlation measurements of CO_2 flux using a closed-path sensor: theory and field tests against an open-path sensor, *Boundary-Layer Meteorol.* **64** (1993), pp. 391–407.

Suyker et al., 2003: A.E. Suyker, S.B. Verma and G.G. Burba, Interannual variability in net CO_2 exchange of a native tallgrass prairie, *Global Change Biol.* **9** (2003), pp. 1–11.

Suyker et al., 2004: A.E. Suyker, S.B. Verma, G.G. Burba, T.J. Arkebauer, D.T. Walters and K.G. Hubbard, Growing season carbon dioxide exchange in irrigated and rainfed maize, *Agric. For. Meteorol.* **124** (2004), pp. 1–13.

Webb et al., 1980: E.K. Webb, G.I. Pearman and R. Leuning, Correction of flux measurements for density effects due to heat and water vapor transfer, *Quart. J. R. Meteorol. Soc.* **106** (1980), pp. 85–100.

West and Post, 2002: T.O. West and W.M. Post, Soil organic carbon sequestration rates by tillage and crop rotation: a global data analysis, *Soil Sci. Soc. Am. J.* **66** (2002), pp. 1930–1946.

Wood et al., 2000: S. Wood, K. Sebastian and S.J. Scherr, Pilot Analysis of Global Ecosystems: Agroecosystems, IFPRI, WRI, Washington, DC (2000).

Wofsy et al., 1993: S.C. Wofsy, M.L. Goulden, J.W. Munger, S.M. Fan, P.S. Bakwin, B.C. Daube, S.L. Bassow and F.A. Bazzaz, Net exchange of CO_2 in a midlatitude forest, *Science* **260** (1993), pp. 1314–1317.

Xu and Baldocchi, 2003: L. Xu and D.D. Baldocchi, Seasonal variation in carbon dioxide exchange over a Mediterranean annual grassland in California, *Agric. For. Meteorol.* **123** (2003), pp. 79–96.

Yang et al., 2004: H.S. Yang, A. Dobermann, J.L. Lindquist, D.T. Walters, T.J. Arkebauer and K.G. Cassman, Hybrid-maize—a maize simulation model that combines two crop modeling approaches, *Field Crops Res.* **87** (2004), pp. 131–154.